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Radio and X-Ray Detectability of Buoyant Radio Plasma Bubbles in Clusters of Galaxies Detectability of Buoyant Radio Bubbles in Clusters of Galaxies Torsten A. Enßlin Sebastian Heinz T. A. Enßlin S. Heinz Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str.1, Postfach 1317, 85741 Garching, Germany today

The Chandra X-ray Observatory is finding a surprisingly large number of cavities in the X-ray emitting intracluster medium (ICM), produced by the release of radio plasma from active galactic nuclei. In this Letter, we present simple analytic formulae for the evolution of the X-ray deficit and for the radio spectrum of a buoyantly rising bubble. The aim of this work is to provide a theoretical framework for the planning and the analysis of X-ray and radio observations of galaxy clusters. We show that the cluster volume tested for the presence of cavities by X-ray observations is a strongly rising function of the sensitivity. Radiation mechanisms: thermal – Radiation mechanism: non-thermal – Galaxies: active – Intergalactic medium – Galaxies: cluster: general – Radio continuum: general

Introductionsec:intro An early key result from the Chandra X-ray observatory was the discovery of numerous X-ray cavities in clusters of galaxies, preceded by pioneering detections by the *ROSAT* satellite. For example, cavities were found in the Perseus cluster 1993MNRAS.264L..25B, the Cygnus-A cluster 1994MNRAS.270..173C,2000MNRAS.318L..65F, the Hydra-A cluster 2000ApJ...534L.135M, Abell 2597 2001ApJ...562L.149M, Abell 4059 1998ApJ...496..728H,heinz2002, Abell 2199 fabian2001moriond, Abell 2052 2001ApJ...558L..15B, close to M84 in the Virgo Cluster 2001ApJ...547L.107F, in the RBS797 cluster 2001AA...376L..27S, and in the MKW3s cluster astro-ph0107557. In most of these cases, the cavities are clearly coincident with the lobes of a radio galaxy at the cluster center. However, some clusters exhibit also cavities without detectable radio emission, namely in Perseus, Abell 2597, and Abell 4059. The latter class of cavities are also believed to be filled with radio plasma, but during the buoyant rise of the very light radio plasma in the cluster atmosphere gull1973,2000AA...356..788C,2001ApJ...554..261C,2001MNRAS.325..676B,astro-ph0201125 adiabatic expansion and synchrotron/inverse Compton radiation losses should have diminished the observable radio emitting electron population, leaving behind a so called *ghost cavity* or *radio ghost* 1999dtrp.conf..275E. The detectability of an X-ray cavity should also decrease with increasing distance from the cluster center due to the decreasing ratio of the missing X-ray emission from the volume occupied by the bubble to the fore- and background X-ray emission.

Rising buoyant bubbles

While the early phase of radio galaxy evolution is characterized by supersonic expansion into the surrounding medium, the radio lobes quickly settle into pressure equilibrium with the ICM after the AGN has shut off. Our description sets in at this moment t_1, where the bubble is located at a cluster radius r_1 with volume $V_{\rm b,1}$ and pressure $P_1 = P_{\rm ICM}(r_1)$. The bubble will then quickly approach a terminal velocity $v_{\rm b}(r)$, governed by the balance of buoyancy and drag forces. During its rise, the bubble volume changes according to the adiabatic law $V_{\rm b}(r) = V_{\rm b,1}\,(P(r)/P_1)^{-1/\gamma_{\rm rp}}$, where the adiabatic index $\gamma_{\rm rp}$ is close to 4/3, which we will take as our fiducial value for numerical examples. The magnetic field strength should evolve according to $B(t) = B_1\,(V_{\rm b}(t)/V_{\rm b,1})^{-2/3} = B_1\,(P(t)/P_1)^{2/(3\,\gamma_{\rm rp})}$, if the expansion of the bubble is isotropic. For simplicity, we only consider spherical bubbles with radius $r_{\rm b}$, which gives sufficiently accurate estimates for most applications. If the bubble becomes highly deformed or even disintegrates, more sophisticated models than ours will have to be used. We further assume, that entrainment of environmental gas into the bubble is dynamically insignificant on the considered time-scales, implying that the bubble is X-ray dark. Numerical simulations [e.g.,][]2001ApJ...549L.179R support the latter.

It is often convenient to express physical quantities like the bubble volume and the magnetic field strength in terms of the values they would have if the bubble were adiabatically moved to the cluster center. We denote these by the subscript 0 (e.g., $V_{\rm b,0} = V_{\rm b}(r=0) = V_{\rm b,1}\,(P_0/P_1)^{-1/\gamma_{\rm rp}}$). As our working example, we will investigate a cluster described by an isothermal β-profile with a density profile of $\rho(r) = \rho_0\,(1+(r/r_{\rm c})^2)^{-3\,\beta/2}$, pressure $P(r) = P_0\,(1+(r/r_{\rm c})^2)^{-3\,\beta/2}$, and constant sound speed $c_{\rm s}\delta$.

We define the origin of the cluster coordinate system at the cluster center, with the x and y axis defining the image plane and the z-axis the line of sight to the observer, and the coordinate system oriented so that the bubble center is located in the x-z plane at $\vec{r} = (r\,\cos\theta, 0, r\,\sin\theta)$. Its projected distance from the cluster center is $R = \mu\,r$, where $\mu = \cos\theta$. The angle θ should be roughly conserved along the bubble's trajectory in a spherical cluster atmosphere.

The buoyancy speed of the bubble can be estimated from the balance of buoyancy and drag forces. The buoyancy force equation $\mathrm{F}_{\mathrm{buoyancy}} = 43\, \pi\, r_{\mathrm{b}}^3\, g\, \rho = 43\, \pi\, r_{\mathrm{b}}^3\, dPdr$